Computer and Centrifuge Modeling of Decoupled Explosions in Civilian Tunnels

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Abstract

Geotechnical structures such as underground bunkers, tunnels, and building foundations are subjected to stress fields produced by the gravity load on the structure and/or any overlying strata. These stress fields may be reproduced on a scaled model of the structure by proportionally increasing the gravity field through the use of a centrifuge. This technology can then be used to assess the vulnerability of various geotechnical structures to explosive loading. Applications of this technology include assessing the effectiveness of earth penetrating weapons, evaluating the vulnerability of various structures, counter-terrorism, and model validation. This document describes the development of expertise in scale model explosive testing on geotechnical structures using Sandia's large scale centrifuge facility. This study focused on buried structures such as hardened storage bunkers or tunnels. Data from this study was used to evaluate the predictive capabilities of existing hydrocodes and structural dynamics codes developed at Sandia National Laboratories (such as Pronto/SPH, Pronto/CTH, and ALEGRA).

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **AUG 1998**	2. REPORT TYPE	3. DATES COVERED **00-00-1998 to 00-00-1998**

4. TITLE AND SUBTITLE **Computer and Centrifuge Modeling of Decoupled Explosions in Civilian Tunnels**	5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Sandia National Laboratories,PO Box 5800,Albuquerque,NM,87185-0751**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR’S ACRONYM(S) 11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM001002. Proceedings of the Twenty-Eighth DoD Explosives Safety Seminar Held in Orlando, FL on 18-20 August 1998.

14. ABSTRACT
see report

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**24**	

1.0 INTRODUCTION

1.1 Motivation

Centrifuges have a 60 year history for the testing of scaled geotechnical structures. Sandia National Laboratories operates two centrifuges, one of which is among the largest dynamic load capacity in the world. Sandia's Large Centrifuge Facility has been used to study topics such as soil permeability, slope stability, mine stability, and more. This study provided an opportunity to develop expertise in the testing of explosive loading on scaled geotechnical structures at Sandia, thus enhancing the unique capabilities of the Large Centrifuge Facility.

The purpose of this study was to verify that gravity scaling laws are valid for explosive events in buried structures and to establish the capability to assess the vulnerability of various geotechnical structures to explosive loading. In particular, methods of combining explosive loading to the steady-state centrifuge acceleration field were investigated. The data gathered from this study were used to evaluate the predictive capabilities of Sandia's phenomenological models and computer codes. The scaled model approach of the centrifuge provided an accurate simulation to validate the models and codes without the expense and risks incurred in full-scale explosive testing.

1.2 Program Objectives

This study was a marriage of the large scale test facilities and the predictive capabilities of computer simulation techniques at Sandia. A Sandia team was assembled to develop a suitable scaled test configuration that could be used to validate existing computer codes and constitutive models that predict the response of full-size earth structures to explosive events. This team included expertise in explosive testing and analysis, geomechanics, material and structural mechanics, and full-scale experiments. For test development, emphasis was placed on problems which complement Sandia's mission. Based on predictions generated by the hydrocodes and structural dynamics codes (Pronto/SPH, Pronto/CTH and ALEGRA), an appropriate class of geotechnical structures was identified for modeling and testing. Focus was placed on ground shock effects on underground structures such as tunnels or covered bunkers. A scaled underground tunnel model was built using existing scaling laws. In order to help develop this testing capability, several tests on the model were performed. These tests included explosive tests with the model not subjected to the centrifuge g-field. The final test on the scaled geotechnical structure included both centrifugal loading and explosive loading. Measured data was compared with the predicted results of existing hydrocodes and structural dynamics codes.

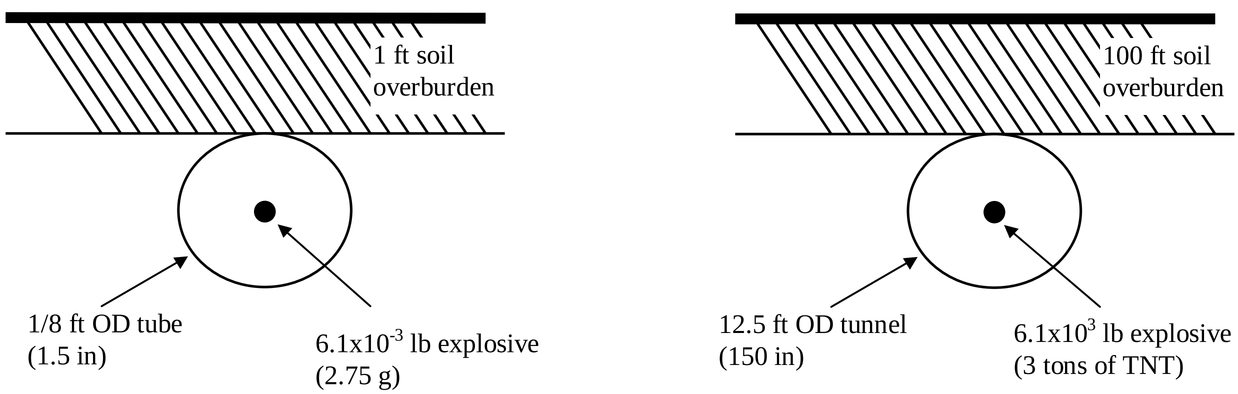
2.0 THE EXPERIMENT PLAN

2.1 Introduction

This project proposed gravity scaling of an explosive event in a steady-state acceleration environment available through centrifuge testing. Many different types of explosive events amenable to gravity scaling were available including: 1) cratering, 2) a scale model building with explosively induced, gravity driven progressive collapse, and 3) tunnels in rock or soil subjected to decoupled explosive loading (Mosaic 1979). After weighing time, budget, and complexity-of-effort constraints, it was decided to focus on a decoupled explosion in a tunnel residing in an engineered soil. This configuration was chosen because length scales directly with gravity on underground structures in regards to stress, deformation, and the physical dimension of the structure.

Based on extensive computer simulation (Section 3), a 1/100 scale model representing approximately a 13-foot diameter tunnel buried about 100 feet in soil was chosen to demonstrate the technique. A 3 gram explosive charge representing about 6600 pounds of TNT (scaled due to the 100 G centrifuge loading) was fired in the center of the tunnel. The experiment configuration consisted of a 2 ft x 2 ft x 2 ft aluminum box containing an engineered soil. A small aluminum pipe (1.5-inch OD) was placed horizontally in the center of the container. The pipe ends protruded through slots in the soil container walls.

Scaled Centrifuge Model at 100 G's **Full Size Representation at 1 G**



The 3 gram explosive charge underwent a proof-of-design test inside a sample section of the aluminum tube (Blanchat et al, 1998, Appendix A). Three explosive tests were performed at the Large Centrifuge Facility (LCF). The first test was a static fire test of the experiment configuration (loaded with engineered soil and partially instrumented) using only a RP-2 detonator. The second test was a static fire test in a load frame of the same experiment configuration using the 3 gram charge. The last test was a dynamic test (on the centrifuge at 100 G) using a newly configured experiment loaded with a new aluminum pipe, engineered soil, complete instrumentation, and a 3 gram charge.

A geotechnical fixture (Blanchat et al, 1998, Appendix B) was designed to withstand the maximum expected centrifuge loading with a >2 safety factor. This fixture underwent a proof pressure test in a static load frame prior to being subjected to the centrifuge loading. A well-characterized engineered soil was fabricated (Blanchat et al, 1998, Appendix C). The 3 gram explosive charge was designed and fabricated (Blanchat et al, 1998, Appendix D) based on extensive code modeling. Based on the code results, accelerometers, strain gages, and pressure gages were installed at specific locations identified to provide code comparison and validation. The primary data acquisition system (DAQ) consisted of Tektronix digitizing oscilloscopes along with appropriate signal conditioning.

2.2 Description Of The Large Scale Centrifuge Facility

Sandia National Laboratories Large Centrifuge Facility (LCF), Figure 2.1, is a state-of-the-art facility in Albuquerque. This facility was developed to simulate loads on weapons components and systems that are produced by missiles and jet aircraft acceleration. Its capabilities also include adaptation for geotechnical experiments. The 29-foot-radius indoor centrifuge has a dynamic load capacity of 1.6 million G-pounds. It can accelerate 16000 pounds to nearly 100 G's, and lighter loads may be accelerated to nearly 300 G's. The centrifuge maximum rotational velocity is 175 rpm due to aerodynamic limits. The indoor centrifuge room has a 12-foot clearance height.

Figure 2.1. Sandia National Laboratories Large Centrifuge Facility.

The Geotechnical Swing-Arm Assembly, Figure 2.2, consists of a pair of swing-arms mounted to pivots that are attached to the centrifuge-arm load-attachment points. The swing-arms allow the geotechnical material to be inserted into a fixture in the normal earth gravitational environment, and then to swing outward due to the centripetal acceleration of the centrifuge. This design allows the resultant acceleration vector to remain in the same orientation as the experiment. The lower end of the swing-arms carry a rigid frame that can accommodate a variety of geotechnical experiment fixtures. The soil fixture used in this experiment is shown securely attached to the rigid frame in Figure 2.2.

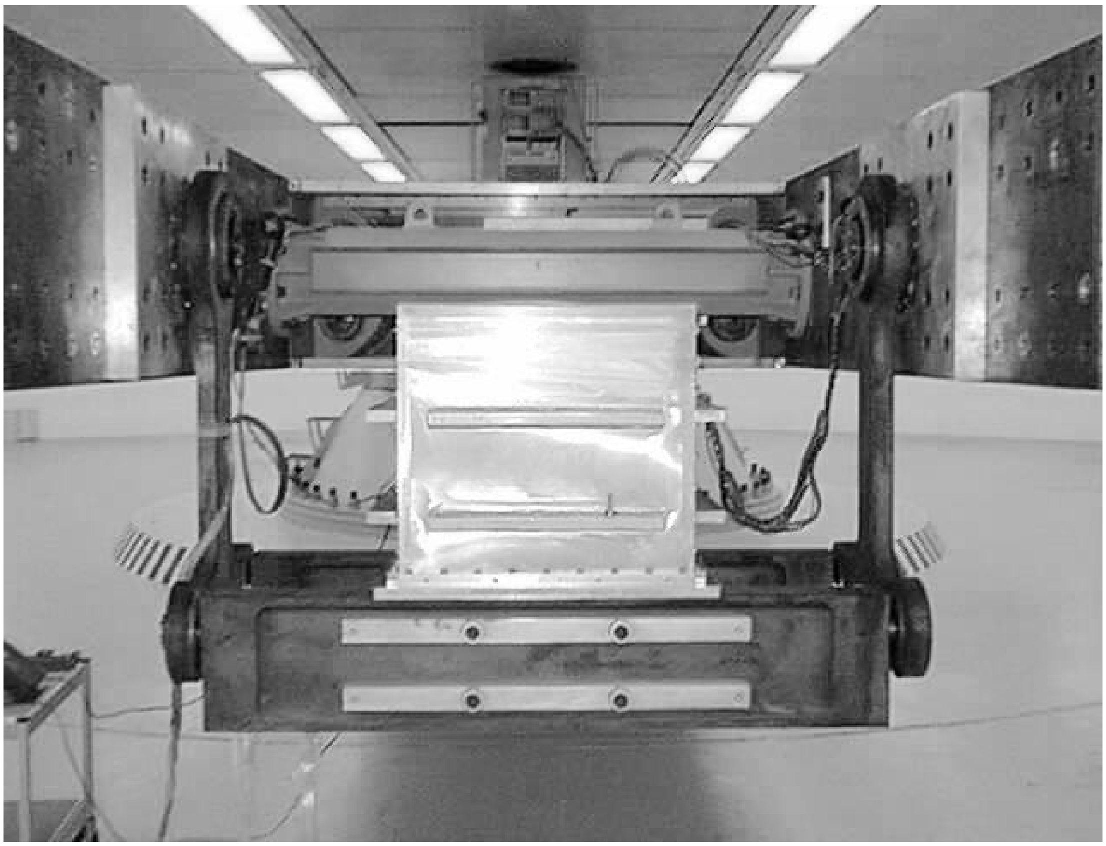


Figure 2.2. The Geotechnical Swing-Arm Assembly.

2.3 Centrifuge Scaling Relations

The relationship between properties in a scale model and those in a full-scale prototype is defined by a set of scaling laws. These laws are derived from dimensional analysis of the hydrodynamic equations that govern the phenomena of interest. Consistent sets of scaling laws have been derived for many such hydrodynamic problems (Gaffney 1983, Schmidt and Holsapple 1980). Table 2.1 gives the scaling factors that have been established for basic soil parameters in centrifuge tests.

Table 2.1. Centrifuge scale factors

Parameter	Scale factor
length	1/G
displacement	1/G
stress	$1/G^2$
strain	1
acceleration	G
time	1/G
energy	$1/G^3$
frequency	G

Similarity conditions are expressed in terms of G-values, assuming that acceleration is scaled at G and the model lengths are scaled at 1/G. Note that Table 2.1 assumes that prototypic material is used in the model, i.e., particle size and density have a scale factor. Note that explosive yields will scale as $1/G^3$ because the specific energy is constant and the total energy is a product of density and length cubed.

In summary, all dimensions of a model needed to represent a full-scale structure scale inversely proportional to the applied G field, and other quantities scale as shown in Table 2.1. For example, at 100 G's, one pound of force on a $1/100^{th}$ scale model is equivalent to 10000 pounds on a full-sized object. One gram of explosives at 100 G's generates an energy level that is equivalent to a million grams, or one metric ton of explosives.

3.0 EXPERIMENT DESIGN USING COMPUTER SIMULATIONS

3.1 ALEGRA

The computer code ALEGRA was used in this study to design the size and thickness of the aluminum tunnel liner and the decoupled explosive charge inside the tunnel. ALEGRA is an arbitrary Lagrangian-Eulerian (ALE) wave code with specific emphasis on large distortion and shock propagation (Budge et al, 1997a, Budge et al, 1997b).

3.2 Preliminary Calculations

Preliminary calculations were performed using a pseudo one-dimensional ALEGRA model. This model treats the explosive, air, tunnel liner and soil as depicted in Figure 3.1. Computational cells or elements in this model are actually two-dimensional axisymmetric but the boundary conditions on the model constrain it to one-dimensional behavior such as observed when a shock wave is transmitted lengthwise through a metal rod. In this model the explosive is shown as magenta, the air blue, the aluminum tunnel liner as green and the soil as yellow. A gravitational acceleration of 100 G in the negative X direction was applied to this model.

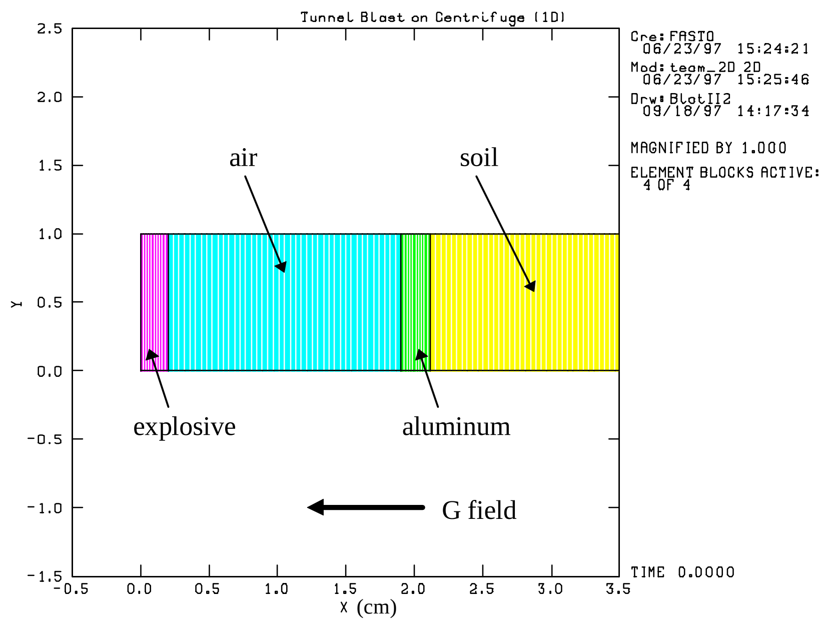


Figure 3.1. Pseudo one-dimensional ALE model used to design the decoupled explosive tunnel experiment. The explosive is represented as magenta; air, blue; aluminum, green; soil, yellow.

A Jones-Wilkins-Lee (JWL) equation-of-state, with a programmed burn, was employed to model the PBX-9407 explosive detonation (Budge et al, 1997a). Parameters necessary to characterize the explosive behavior during detonation are given in Table 3.1.

A soil/compressible-foam constitutive model was used to model the engineered soil compacted around the aluminum pipe. Table 3.2 contains the single-value parameters associated with the material model and Table 3.3 shows the pressure versus volumetric strain relationship necessary for the model.

Table 3.1. JWL equation-of-state parameters for PBX-9407

Parameter	Value	Units
reference density	101.12	lb/ft^3
a	8.31e7	psi
b	2.08e6	psi
c	1.74e5	psi
omega	0.32	
r1	4.6	
r2	1.4	
cj pressure	3.84e6	psi
detonation velocity	2.59e4	ft/s
cj temperature	4962	K

Table 3.2. Soil and crushable foam constitutive model parameters for engineered soil

Parameter	Value	Units
initial density	86.95	lb/ft^3
bulk modulus	2.90e3	psi
shear modulus	9.28e-3	psi
a0	5.51e5	
a1	0.95	
a2	0.00	

Table 3.3. Pressure versus volumetric strain for engineered soil

Volumetric Strain	Pressure (psi)
6.0000e-3	3.47
0.0200	6.94
0.0640	13.88
0.1140	27.69
0.2231	50.68
0.2400	55.48
0.2600	83.27
0.2700	110.96
1.0000	2154.28

An elastic-perfectly-plastic constitutive model was employed to model the aluminum tube that served as the tunnel liner after the emplacement of the soil around the tube. The constitutive model parameters selected for aluminum are given in Table 3.4.

Table 3.4. Elastic-perfectly-plastic constitutive parameters for aluminum tube

Parameter	Value	Units
Youngs modulus	9.99e6	psi
Poissons ratio	0.334	
yield stress	4.00e4	psi
hardening modulus	1.48e5	psi
beta	1.0	

The final material behavior model necessary for this simulation was for the air that decoupled the explosive from the tunnel liner. This was treated as an ideal gas with parameters given in Table 3.5.

Table 3.5. Ideal gas parameters for air

Parameter	Value	Units
reference density	0.08	lb/ft^3
gamma	1.4	
reference temperature	288.2	K
cv	0.7178e4	

Variables that could be adjusted in this model included: 1) explosive radius, 2) tunnel radius, and 3) tunnel liner thickness. A tunnel diameter of 1.5 inches was chosen based on the general physical dimensions of the existing centrifuge swing-arm which constrained the size of the container holding the tunnel experiment. The container was sized to be a cube two feet on each side. The two foot depth with the tunnel in the center dictated one foot of soil above and below the tunnel. Experience indicated that the tunnel diameter should be approximately 1/10 the length of the soil surrounding it to control the influence of the upper (free) surface and lower (fixed) surface. The tunnel diameter was thus set at 1.5 inches.

A steady-state acceleration environment of 100 G on the centrifuge produces the same stresses and deformations in the soil and tunnel as would be observed in a model with all lengths multiplied by 100. This model thus simulates a 150 inch (12.5 feet, 3.8 m) diameter tunnel buried 100 feet (30.5 m) deep.

Experience indicated that the diameter of the explosive would be an important explosive parameter influencing the effect on the tunnel liner. This was proven later by both the two-dimensional calculations and the experiment itself. Thus, with tunnel diameter and depth-of-burial already determined, the two variables that could be adjusted in the experiment were explosive diameter and tunnel liner thickness.

It was decided that the criteria for controlling the combination of explosive diameter and tunnel liner thickness should be measurable plastic deformation of the tunnel liner resulting from explosive detonation inside the tunnel. The tunnel liner thickness and explosive diameter were both constrained by the commercially available sizes. A number of simulations were performed with several combinations of explosive diameter and tunnel thickness using ALEGRA and the pseudo one-dimensional model. The best combination arrived at was a tunnel liner thickness of 0.083 inches (0.2108 cm) and an explosive diameter of 0.1875 inches of PBX-9407. The length of the explosive was set at 3.75 inches (9.525 cm) which resulted in a total explosive weight of 2.75 g. At a steady-state acceleration environment of 100 G on the centrifuge, this small explosive is equivalent to about 6000 lb of TNT. A schematic of the experimental design is shown in Figure 3.2

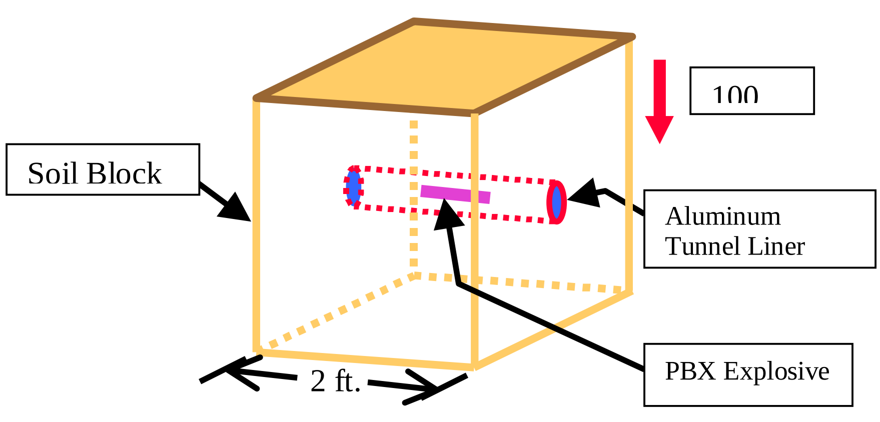


Figure 3.2. Experimental design determined using pseudo one-dimensional ALE model.

3.3 Detailed Two-Dimensional Simulations

All of the design parameters discussed above were employed in a more detailed two-dimensional (x - tunnel diameter, y - tunnel length) axisymmetric model of the tunnel experiment on the centrifuge. A close-up of the two-dimensional axisymmetric ALE model is shown in Figure 3.23 In this model the explosive is displayed in magenta, air blue, aluminum green and soil yellow, the same as the one-dimensional model of Figure 3.1. The material models for the explosive, air, aluminum and soil used in the two-dimensional model are exactly the same as those given above for the pseudo one-dimensional model. Detonation of the explosive is designated to occur along the line on the bottom of the explosive. This model also has a gravitational acceleration of 100 G in the negative X direction.

Pressure caused by the detonation of the explosive and the deformation of the aluminum liner from times 0.0 to 245 micro-seconds (μs) is shown in Figures 3.4 through 3.13. In these plots the pressure corresponding to red has been set at 1.0E9 dynes/cm^2 (14500 psi) Pressures greater than this value are also plotted as red. The actual maximum pressure and its location are shown with symbols on the plot and the value corresponding to the symbol is given below the color bar. A number of very interesting phenomenon can be observed in this series of figures. In Figure 3.5 (25 μs) the air is being pushed ahead of the explosive gas because of the large density difference between the two. In Figure 3.6 (29 μs) the air has been compressed by the explosive gas against the aluminum liner and begins to rebound as illustrated in Figures 3.7-3.8. In Figure 3.9 (39 μs) the air is reconverging in the center of the tube where the explosive was before detonation. Thus, the shock wave marking the separation between the air and explosive gas reverberates a number of times in the tube. The majority of the energy imparted to the tube resulting in plastic deformation is expended during the initial impact of the explosively induced shock wave on the aluminum tube. Plastic deformation of the tube can be seen starting as early as 29 μs. Transmission of the explosively induced shock wave through the tunnel liner and into the soil is observed in Figure 3.12 and especially in Figure 3.13 where the plotting pressure range has been significantly reduced to highlight lower pressures. The final predicted deformed shape of the tube is shown in Figure 3.14. The tube flare is the same length as the explosive and the outward displacement is constant indicating that the pseudo one-dimensional ALEGRA model used for the design of this experiment was an acceptable approach. The final outward radial displacement predicted by the one-dimensional model was 0.24 cm compared with 0.14 cm calculated from the two-dimensional model. The explosive design proof test was performed with the explosive charge detonated inside an aluminum tube that was wrapped with rubber (Blanchat et al, 1998, Appendix D). The outward radial displacement of the tube in the proof test was 0.15 cm.

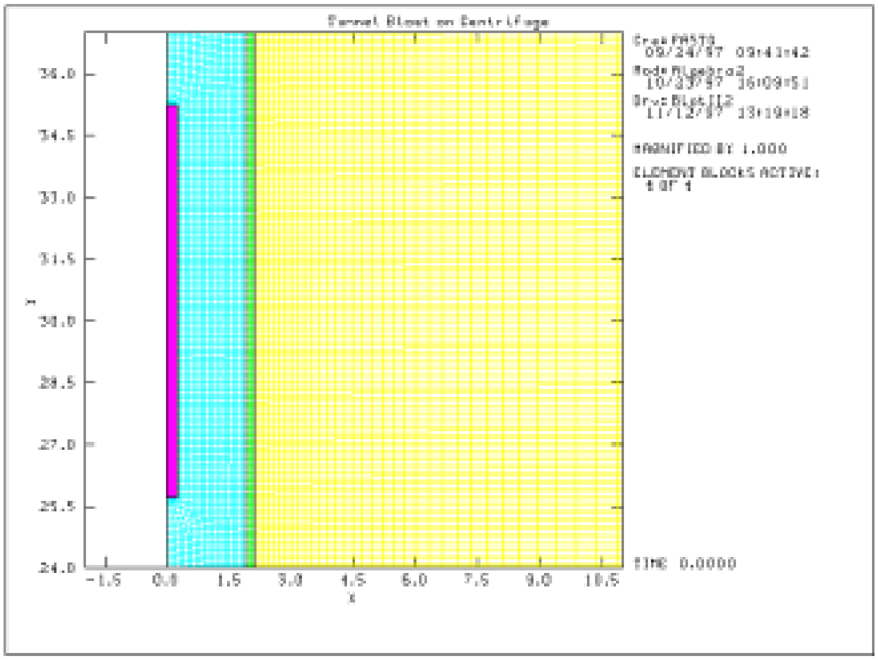


Figure 3.3. Two-dimensional ALE model used to predict the response of the model to a decoupled explosive in a tunnel.

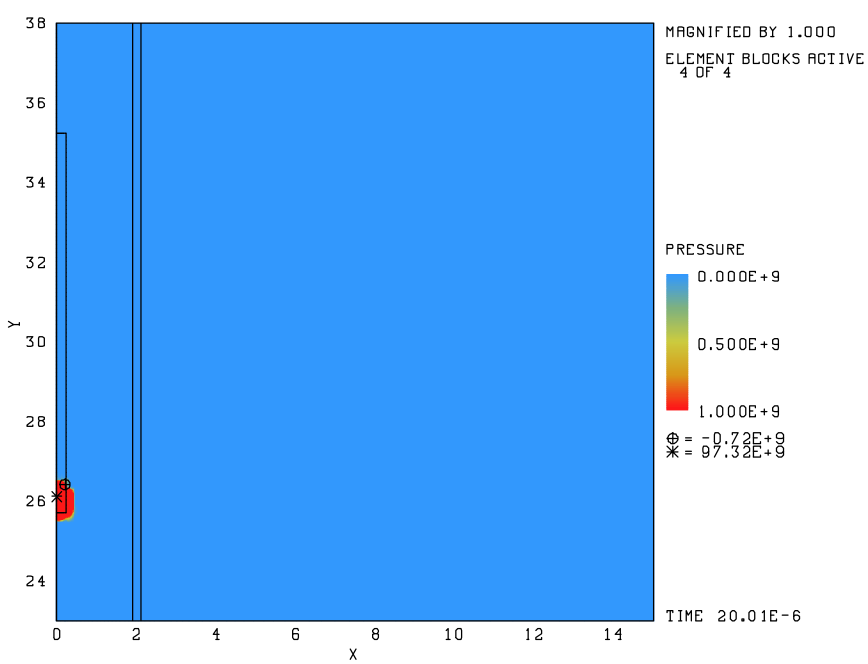


Figure 3.4. Pressure induced by the explosive at 20 μs.

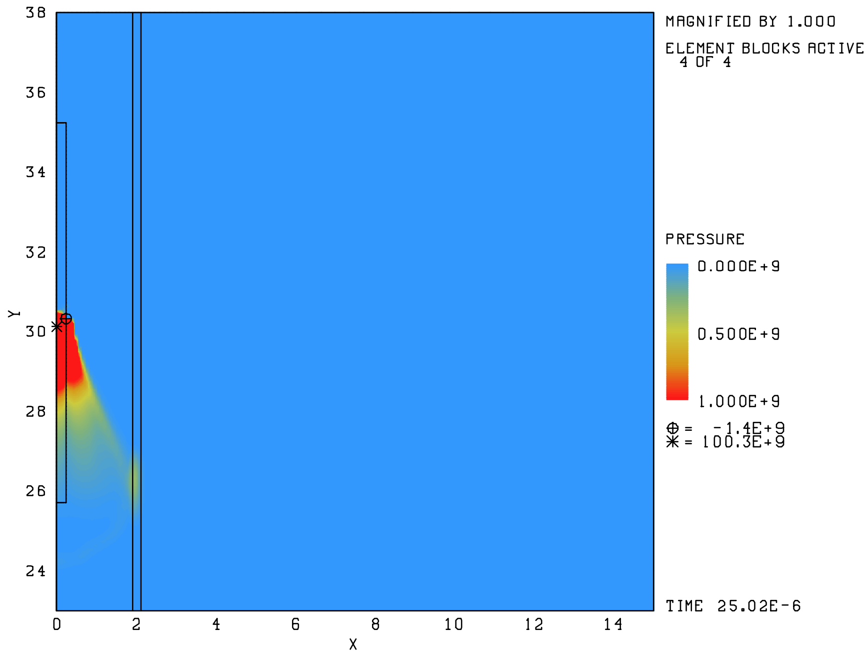


Figure 3.5. Pressure induced by the explosive at 25 μs.

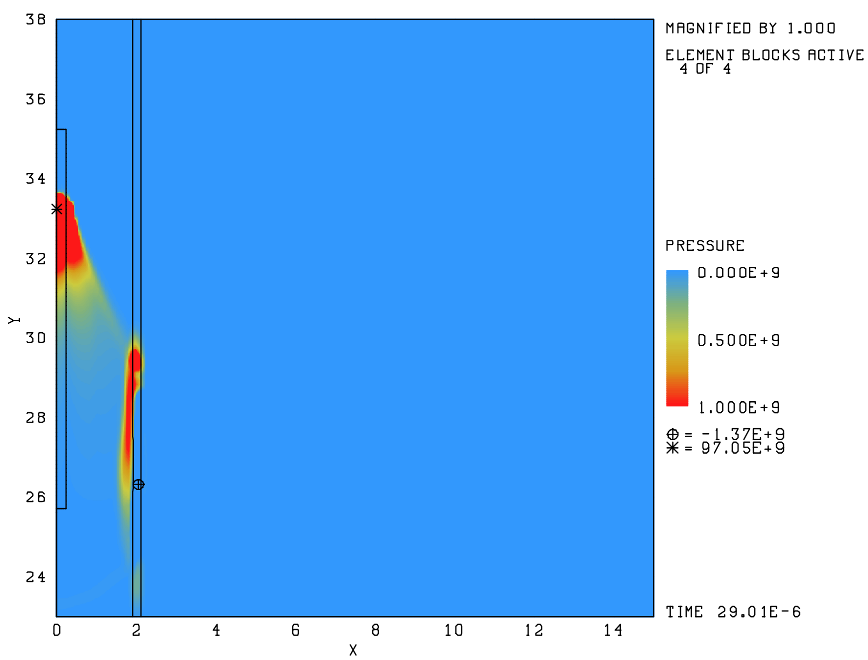


Figure 3.6. Pressure induced by the explosive at 29 μs.

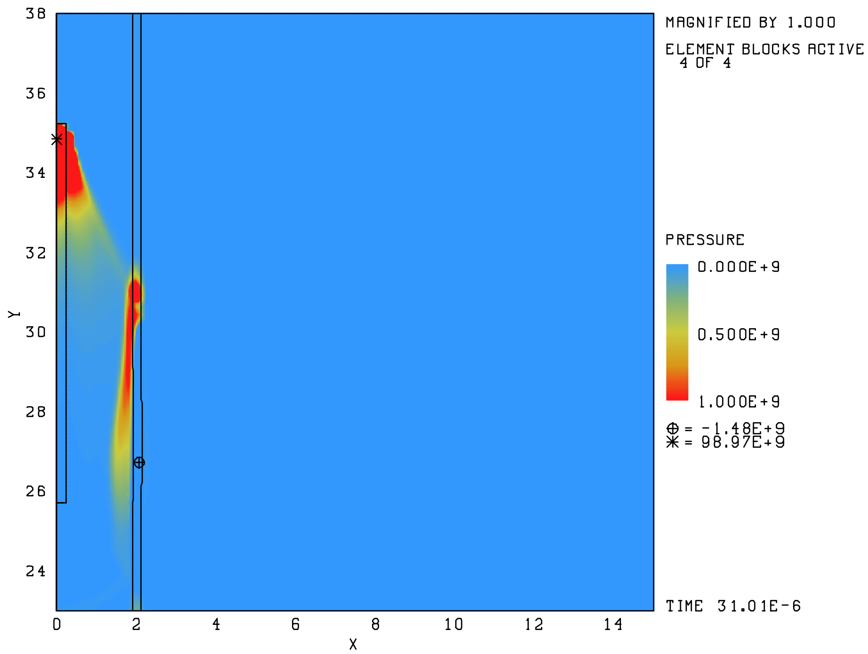


Figure 3.7. Pressure induced by the explosive at 31μs.

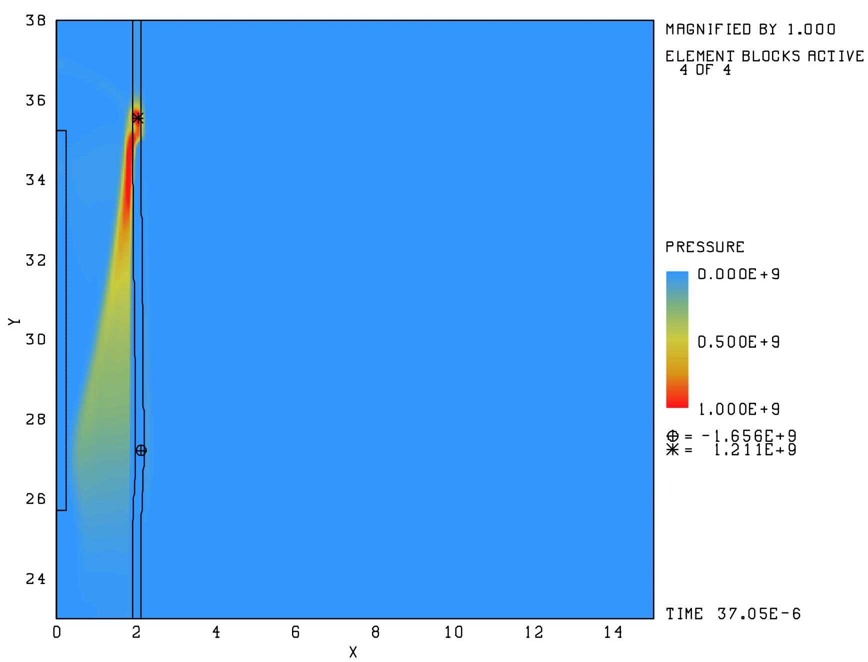


Figure 3.8. Pressure induced by the explosive at 37 μs.

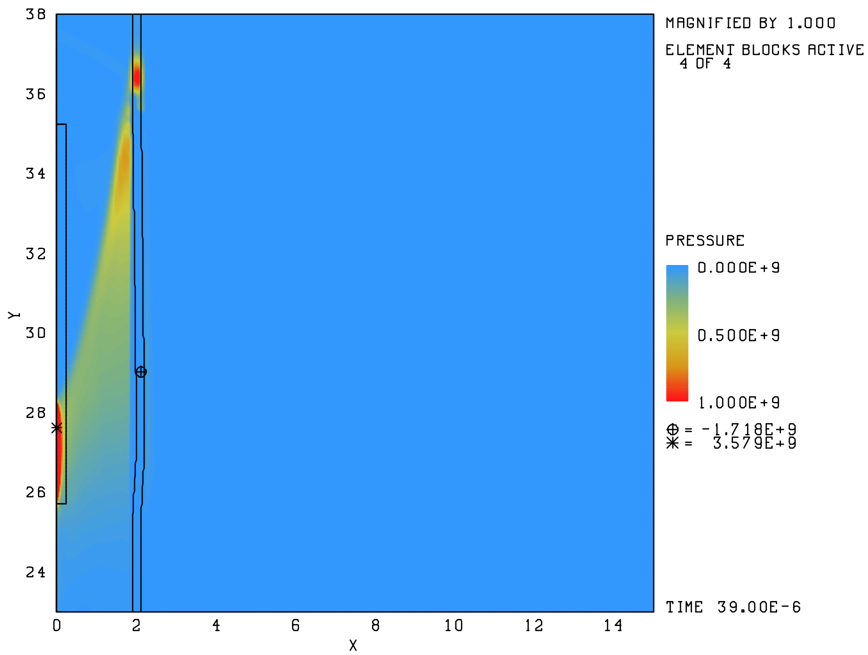


Figure 3.9. Pressure induced by the explosive at 39 μs.

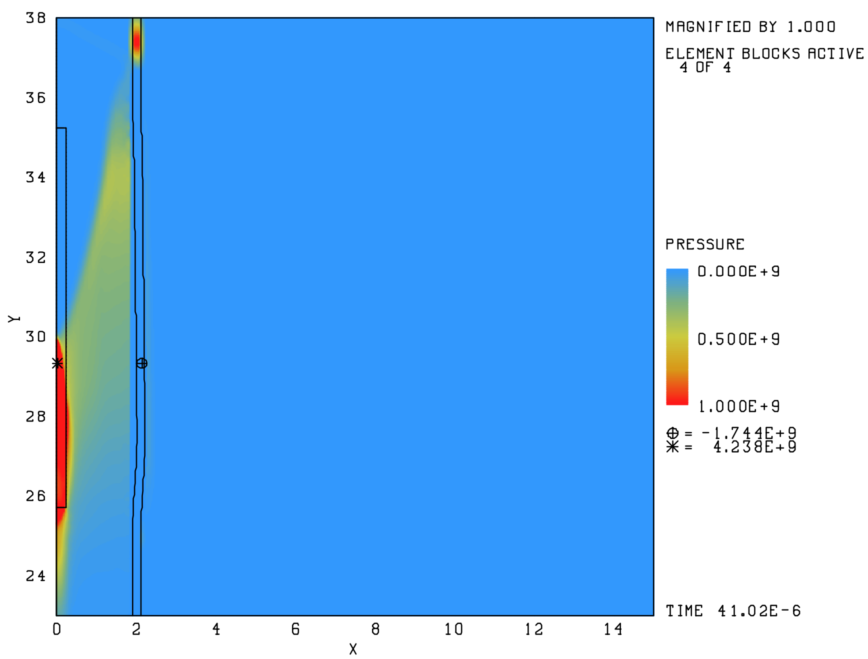


Figure 3.10. Pressure induced by the explosive at 41 μs.

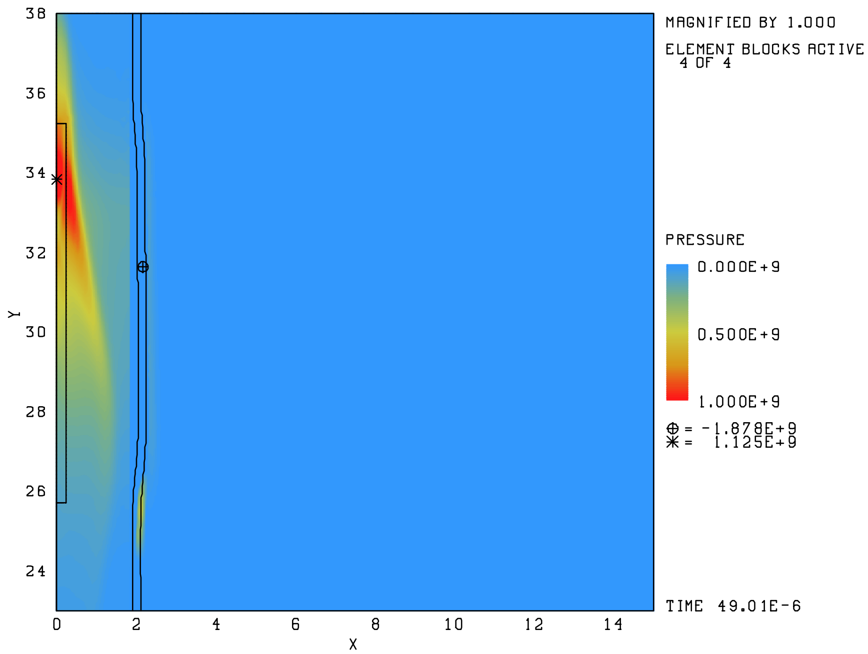


Figure 3.11. Pressure induced by the explosive at 49 μs.

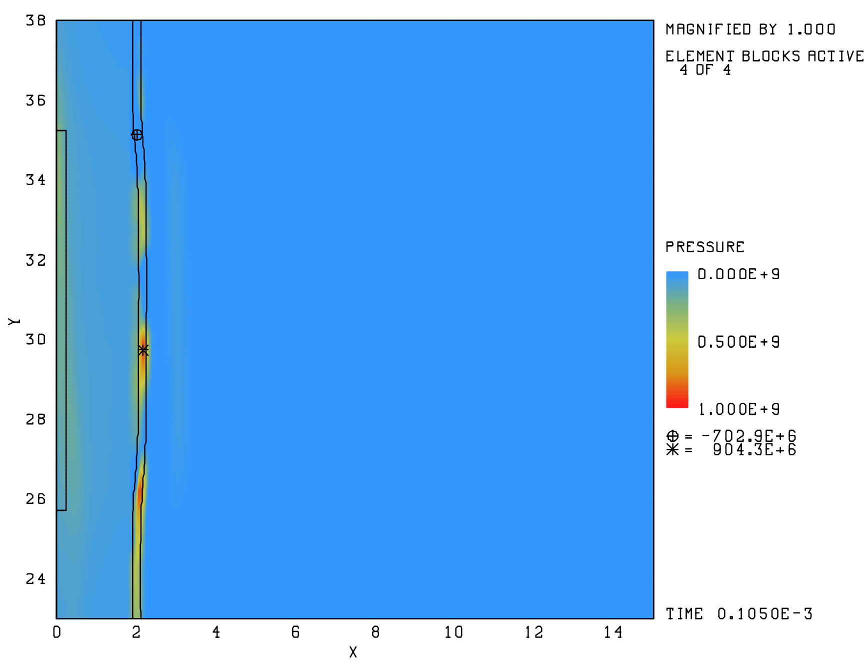


Figure 3.12. Pressure induced by the explosive at 105 μs.

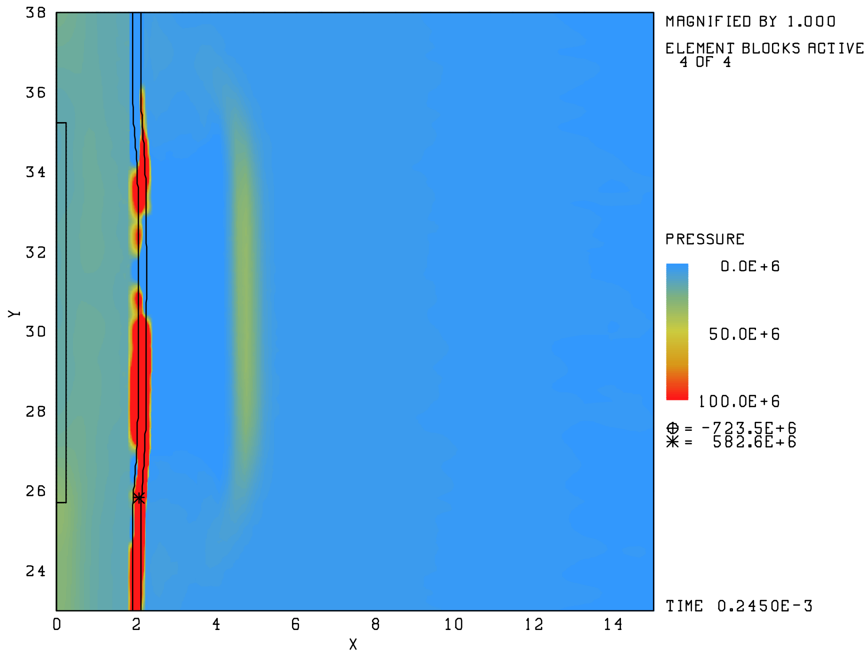


Figure 3.13. Pressure induced by the explosive at 245 μs. Note the difference in the pressure range to highlight the shock wave moving outward through the soil.

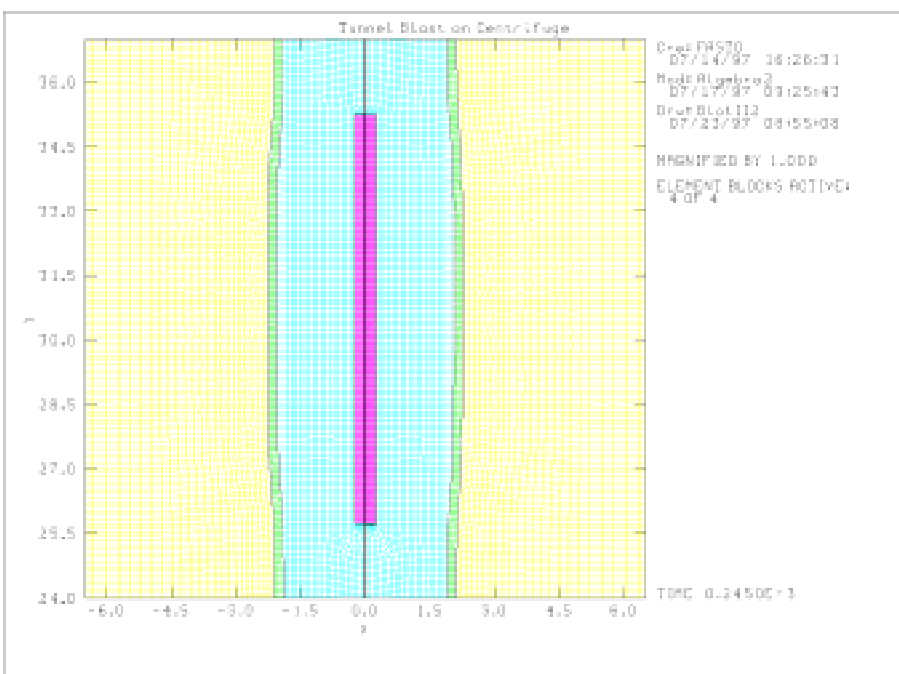


Figure 3.14. Final deformed shape predicted for the aluminum tube.

4.0 EXPERIMENTAL ACTIVITIES

4.1 Introduction

Experimental data were recorded during the experiment for comparison with computer simulations using the ALE code ALEGRA which has been discussed earlier. Instrument locations were determined from the results of the pseudo one-dimensional calculations discussed in section 3.2. Based on the experiment and instrumentation design calculations it was determined to include the following instrumentation: 1) accelerometers at several distances from the tunnel liner, 2) a pressure gauge on the inside of the liner, 3) strain gauges on the outer surface of the tunnel liner in both the hoop and longitudinal directions. Output from these gauges is compared to computer predictions. Details and challenges associated with the instrumentation can be found in Blanchat et al, 1998.

4.2 Transducers

The following types of transducers were used for the indicated measurements:

Soil acceleration	Endevco 7270A piezoresistive accelerometers (200K or 60 K range)
Aluminum tube strain	Micro-Measurements EP-08-250BF-350 high elongation strain gage
Aluminum tube OD radial pressure	Dynasen PC300.50.EKRTE carbon pressure gage

The strain gages and carbon pressure gage were bonded to the aluminum tube near its midpoint, using Micro-Measurements M-Bond AE-10 epoxy. After the adhesive cured, the strain and pressure gages were covered with four layers of electrical tape to help distribute soil loads and minimize the possibility of damage from soil particles. The accelerometers were buried in the soil at various radial distances from the tube. The following sections contain more details on the location of the accelerometers

4.3 100 G Centrifuge Test with 3 Gram Charge

During this full scale test the soil container complete with instrumentation (two strain gages and a pressure gage on the tube, and five accelerometers in the soil) was brought up to 100 G acceleration loading on the centrifuge and the PBX explosive was detonated. Figure 4.1 shows the location of the transducers for this assembly.

Following the test, the soil and tube were removed from the container. Figures 4.2 and 4.3 show the tube, which exhibited radial expansion, and longitudinal tearing that was not predicted by the pre-test computer models. This longitudinal tearing was caused by the soil compacting more in

the center of the container than at the edges. The soil at the edges of the container compacted less due to the friction between the soil and the container . The middle of the tube was bent downward by about 0.25 inches. The tunnel liner thickness and explosive diameter were chosen during the experimental design calculations to produce a significant and measurable flare in the aluminum tube. The extra strain in the bottom of the tube produced by the bending was enough cause the aluminum to rupture.

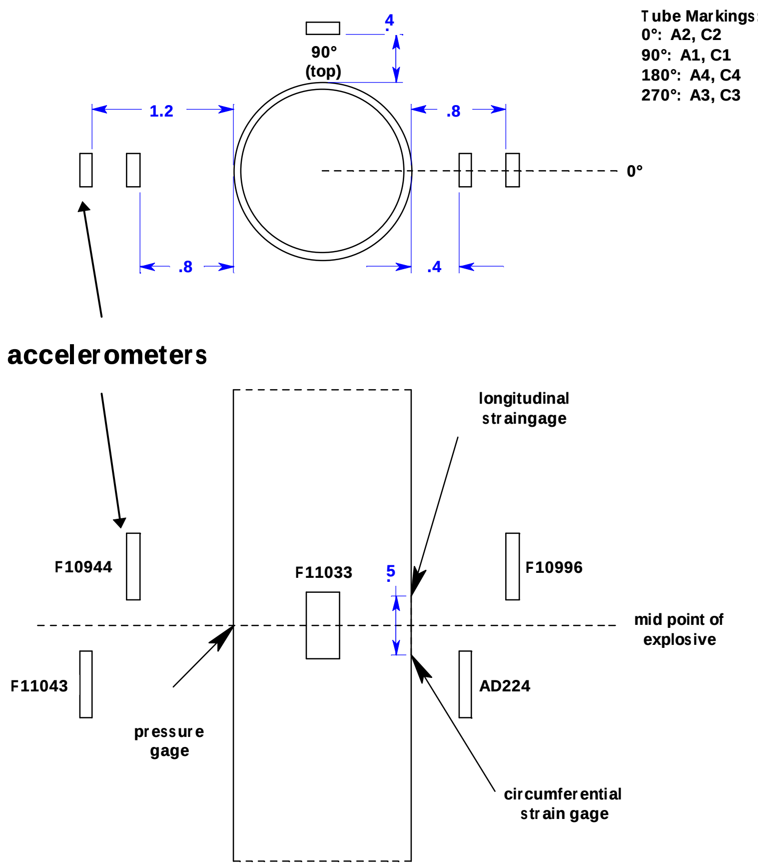


Figure 4.1. Transducer locations for 100 G centrifuge test.

Figure 4.2. Radial expansion of the tube.

Figure 4.3. Unpredicted longitudinal tearing of the tube.

4.7 Experimental Results and Analytical Model Predictions

Figures 4.4, 4.5, 4.6, and 4.7 compare the measure data for acceleration, hoop strain, longitudinal strain, and tube wall pressure, respectively, to that predicted by the computer simulation.

The measured accelerations shown were multiplied by a factor of 4 for the comparison with the analytical results shown in Figure 4.4. This factor was applied to the measured data because the analytical model does not include an accelerometer in the soil. The accelerometer is approximately 4 times heavier than the equivalent volume of soil, so the measured accelerations would be about 4 times lower than the analytically predicted soil accelerations. This correction assumes that the soil pressures are not significantly affected by the presence of accelerometer.

The measured peak acceleration was different by a factor of 2-3 at transducers located close to each other. One possible reason for the difference was that the face of the transducer may have shifted from a normal axis (to the explosive) as the soil compacted prior to the detonation.

Another interesting point was that the measured acceleration close to the tube (at 0.4 inches) was greater than predicted by the computer model and that the measured acceleration father from the tube (at 1.2 inches) was less than predicted. This implied that the "damping" of the shock wave in the soil was greater than that predicted.

Figures 4.5 and 4.6 show that the measured tube hoop and longitudinal strain closely matched predicted values. Figure 4.7 shows that the measured tube wall pressure history also closely matched predicted values. As an aside, predicted soil pressure at an element next to the wall is also plotted in Figure 4.7. Note that the soil pressure is drastically decreased, due to the collapsing behavior exhibited by the soil.

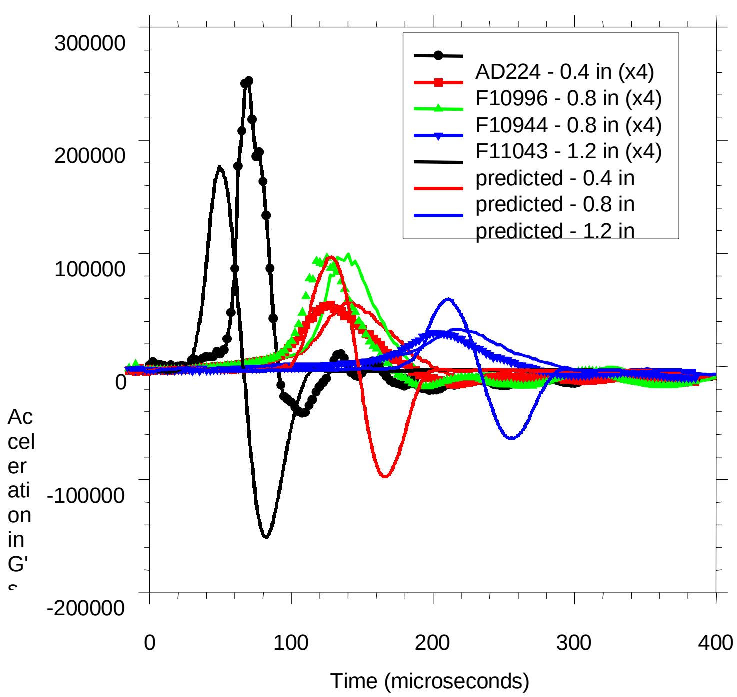


Figure 4.4 Acceleration versus time at various locations .

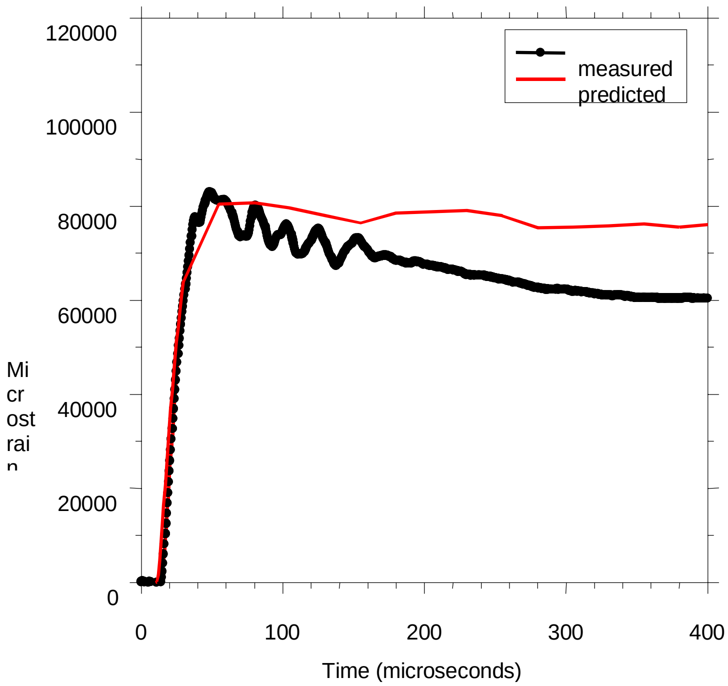


Figure 4.5. Hoop strain versus time.

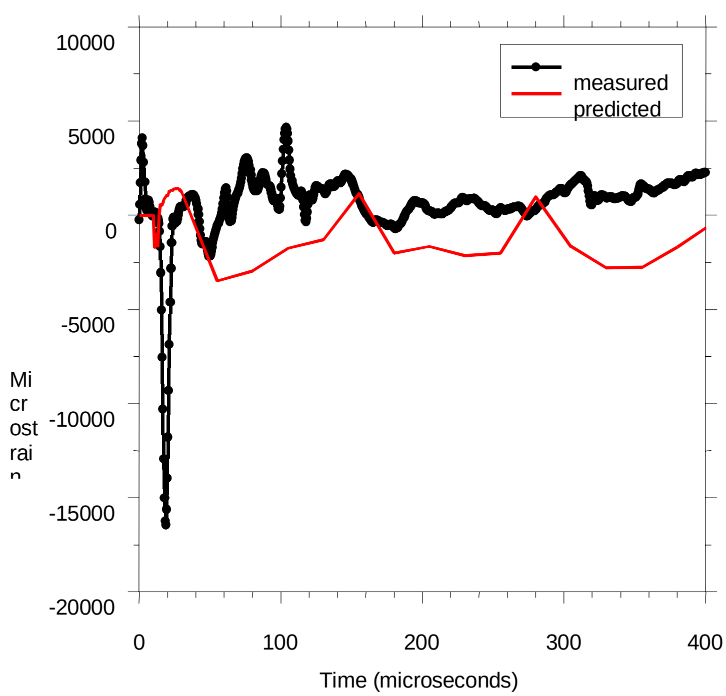


Figure 4.6. Longitudinal strain versus time.

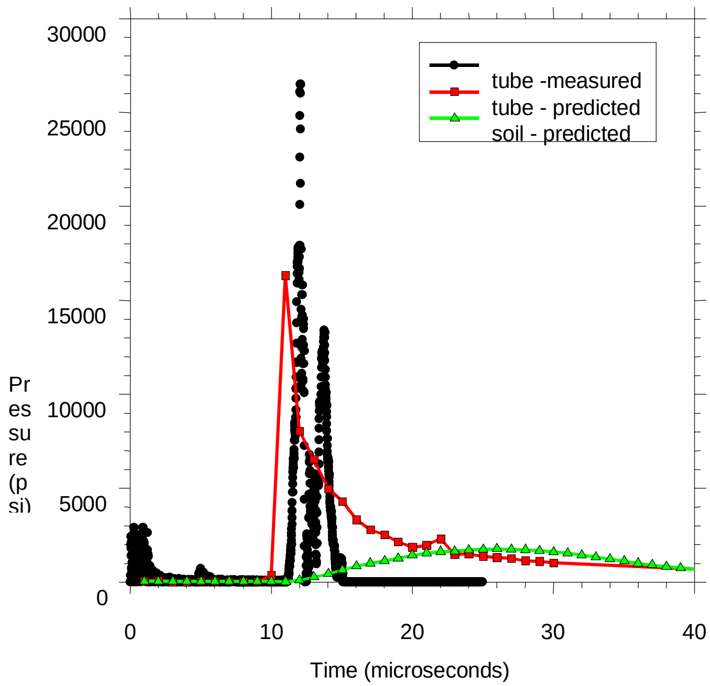


Figure 4.7. Wall pressure versus time.

10.0 CONCLUSIONS

Expertise in the testing of explosive loading of scaled geotechnical structures, utilizing the unique capabilities of the Large Centrifuge Facility, was developed. Considerable dialog and cooperation between computational and experimental departments resulted in a successful program. Sandia's hydrocodes, dynamics codes, and soil models were key elements in the experimental design. Pretest numerical calculations were performed to assess the vulnerability of a metal-lined subterranean tunnel that was subjected to an explosive event. An experiment was performed that validated the following hypothesis: gravity scaling laws are valid for explosive loading of scaled structures in a steady-state centrifugal acceleration field. The experiment provided data to help evaluate the predictive capabilities of existing hydrocodes and structural dynamics codes developed at Sandia.

Most of the measured data compared very well with the pretest blind computer simulations. Discrepancies between observed and predicted soil acceleration magnitudes were explained by the different equivalent masses between the soil and the physical transducers (that were not explicitly modeled in the computer simulations). This error could be reduced by either modeling the instruments or by using transducers with similar mass properties for the media of interest.

The experimental techniques and core knowledge developed under this program can now be applied to more sophisticated problems. Realistic geotechnical structures, such as underground bunkers, tunnels and building foundations, and actual stress fields produced by the gravity load

on the structure and/or any overlying strata can be tested. These stress fields may be reproduced on a scale model of the structure by proportionally increasing the gravity field through the use of a centrifuge. Further study would focus on both buried structures such as hardened storage bunkers or tunnels *in rock mediums* and also above ground structures. This technology can then be used to assess the vulnerability of various geotechnical structures to explosive loadings (such as car bombs in basement garages). Applications of this technology include assessing the effectiveness of earth penetrating weapons, evaluating the vulnerability of various structures, counter-terrorism, and model validation.

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